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Impact of Langmuir isotherm on production behavior of CBM reservoirs

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IMPACT OF LANGMUIR ISOTHERM ON PRODUCTION BEHAVOIR OF CBM RESERVOIRS

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ABSTRACT

IMPACT OF LANGMUIR ISOTHERM ON PRODUCTION BEHAVOIR OF CBM RESERVOIRS.

Efundem Ndipanquang Arrey

Coalbed Methane is an unconventional gas resource that consists of methane production from the coal seams. CBM reservoir performance is also influenced by the interrelationship of reservoir, geologic, and operation parameters. Coalbed methane production performance is considered complex and difficult to analyze especially at the early stages of recovery.

This study was conducted to develop type curves which predict the impact of Langmuir Isotherms on production behavior on a Coalbed Methane reservoir in order to evaluate the economic feasibility and to maximize potential recovery. In order to achieve this objective, the impact of Langmuir isotherm constant on production type curves was studied. Subsequently, a new set of type curves were developed. The type curves can be used to predict the performance of CBM reservoir. However, the value peak gas rate is needed to convert dimensionless gas rate and time predicted by type curves to actual gas rates and real time. Therefore a correlation between peak gas rate and Langmuir constant was developed.

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DEDICATION

I dedicate my work to the Almighty God for giving me a second chance in life and also to all those who have been given a second chance.

I also dedicate my work to my extraordinary parents. Dad, Mum, I could never ask for better parents, thank you for having me.

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CHAPTER I

INTRODUCTION

Coalbed Methane (CBM) is an unconventional gas resource produced from coal seam reservoirs usually at shallow depths with low permeability. The extraction of Coalbed methane began as an effort to reduce the threat of methane explosions in coal mines.
The gas produced contains mostly Methane and small amounts of other hydrocarbons such as hydrogen, carbon monoxide, carbondioxide and nitrogen. CBM was never considered an important source of energy until the early 1980's when it started growing.
Coal bed Methane currently accounts for 8% of US annual gas production and approximately 12% of estimated total US natural gas reserves. Coalbed Methane proven reserves have increased from 3.7 Tcf in 1989 to 18.5 Tcf in 2002 and are expected to increase further as more resources are discovered.

The Appalachian Basin accounts for about 10% of US CBM resources. The Northern Appalachian Basin which covers part of West Virginia, Pennsylvania and Ohio is one of the most potential CBM basins in the United States with an estimated 61Tcf of gas resource. However CBM production is very limited in the Appalachian Basin because operators suffer from the lack of scientific tools that could help them in the development of CBM reservoirs. The contribution of CBM to overall mix of natural gas resources in the US is expected to increase but that would not be the case without substantial increase in the CBM production in the Appalachian Basin.

CBM reservoirs are characterized by a dual porosity system consisting of ***Macropores***: which are also known as cleats constitute the natural fracture common to all coal seams and ***Micropores*** also known as matrix or the primary porosity system which contains the vast majority of the gas in absorbed state. Because of its large internal surface area, coal stores about 6 to 7 times more gas than the equivalent rock volume of a conventional gas reservoir.

Coal is a material rich in carbon that has been formed by the chemical and thermal alterations of organic debris which is buried, compressed, and dewatered. At initial conditions CBM reservoirs are usually water saturated, so in order to produce gas, the water has to be removed from the cleat system first by lowering hydrostatic pressure. This reduction in pressure allows the gas to be released from the matrix by desorption. During dewatering process, the gas desorbs from the coal, gas saturation increases and water saturation decreases. The desorption process is described by the Langmuir isotherm which relates the capacity of the coal to store gas to the external pressure of the gas. At low pressures the relationship between storage capacity and pressure is linear and is referred to as Henry's Law isotherm. While at very high pressures, the storage capacity will reach its maximum.

Analyzing the production performance in CBM reservoirs in the early stages is very challenging. A variety of type curves have been developed previously which could be used to predict production performance of CBM reservoirs. These type curves however assume a typical isotherm and hence do not account for the impact of Langmuir isotherms on production behavior of CBM reservoirs.

CHAPTER II

LITERATURE REVIEW

Natural gas is one of the cleanest and safest sources of energy commonly used today and it is a combustible mixture of hydrocarbon gases. Unconventional gas reservoirs are, such as CBM, more expensive to extract due to the lack of technology. However the increasing demand of energy has resulted in the development of unconventional sources of natural gas. The advancement of technology in reservoir characterization, simulation and production are the key factors that have enhanced the development of CBM reservoirs of the unconventional resources (Schraufnagel, 1994).

2.1 Coalbed Methane

Much research has been conducted on gas resources in coal including the composition of coalbed methane gas, gas retention by adsorption and the gas content of coals. However, probably, the least understood aspect is the generation of coalbed gas. Because gas generation occurs over millions of years, it cannot be readily investigated.

2.1.1 Gas generation and Composition

Coal bed gas though composed primarily of methane includes other gases such as hydrogen, carbon monoxide, carbondioxide, and nitrogen. When peat is formed methane and other gases are produced first by anaerobic fermentation, bacterial and fungal alteration and later in the process of coalification by geochemical alterations through heat and pressure. The gaseous hydrocarbon generated in greatest quality is methane. The process of peat formation and coalification increases carbon in the coal because of the loss of hydrogen and oxygen in the expelled moisture and volatiles. Volatiles produced include water (H_2O), carbondioxide (CO_2), methane (CH_4), Nitrogen (N_2) and heavier

hydrocarbonate. More of these volatiles are retained during coalification than during peat formation because of the higher pressure from overlying sediments.
Moisture content decreases as coal rank increases, thus most of the water produced during coalification (in addition to original moisture) is expelled from the coal.

2.1.2 Gas retention by adsorption

One characteristic that makes coal reservoir different from conventional gas reservoirs is the manner in which the gas is stored. In the conventional reservoir, the gas exist in a free state in the pore of the reservoir rock, while nearly all of the gas in a coal exist in a condensed near liquid-like state because of physical sorption. Gases also are present in coal beds as free gas within the pores or fractures and/or dissolved in solution (groundwater) within the coal bed. Physical adsorption of methane in coal is caused by weak attractive forces (van der waals forces) that exist between pairs of molecules or atoms. Adsorption increases non-linearly with pressure and is reversible by increasing the temperature or decreasing the pressure.

2.1.3 Transportation Mechanism:

Most of the gas present in coal seams is physically adsorbed on the internal surfaces of the unfractured coal matrix. Gas production from coals, occurs by a three -stage process in which gas

1) Diffuses through the coal matrix to the cleats.
2) desorbs from the cleat surfaces (natural fractures)
3) flows from natural fractures

This process is shown in Figure 2.1

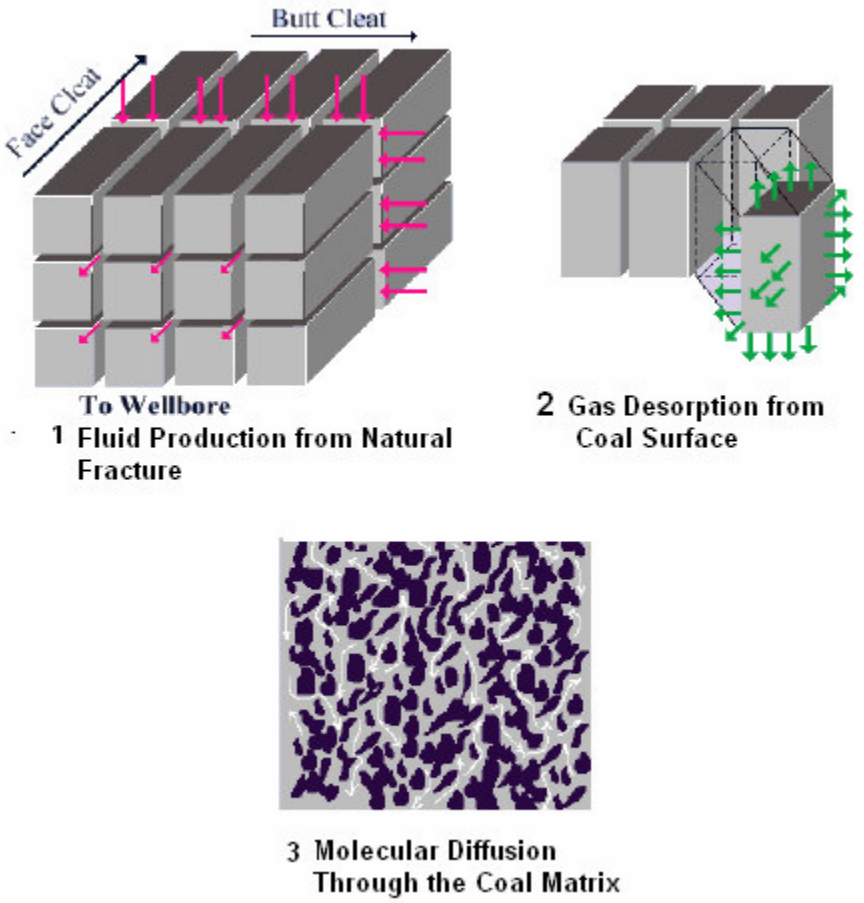

Figure 2.1: Transport Mechanism in a Coal Matrix

2.1.3.1 Desorption

This is the process by which methane molecules detach from the micropore. Surfaces of the coal matrix and enter the cleat systems where they exist as free gas. The desorption Isotherm defines the relationship between the adsorbed gas concentration in the coal matrix and the free gas pressure in the coal cleat systems. In the desorption stage, the desorption Isotherm is the link between the flow in the matrix systems (where flow is controlled by concentration gradient and flow in the cleats system systems (where flow is controlled by pressure gradient). The relationship between gas concentration and pressure is a non-linear function that is generally defined by the Langmuir Equation 2.1 shown below.

$$C_m = V_L \frac{P}{P_L + P}(0.03\rho_B) \quad \text{.....(2.1)}$$

Where

C_m = matrix gas concentration, SCF/ft^3

V_L= Dry, ash-free Langmuir volume constant Scf/ton

P =Pressure in fracture systems, psia.

P_L= Langmuir pressure constant psia

ρ_B = Bulk density, g/cm^3

The Langmuir constants for a particular coal are determined in the laboratory.

2.1.3.2 Diffusion:

This is a process in which flow occurs through, random molecular motion from an area of high concentration to an area of low concentration. The process of diffusion of methane in a coal matrix is shown in Figure 2.2

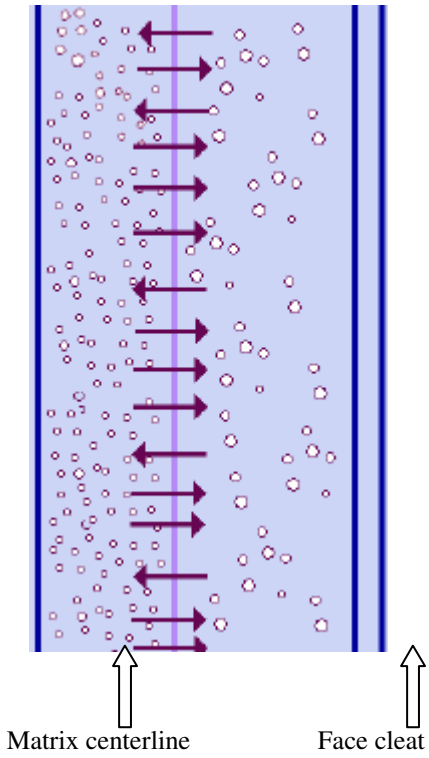

Figure 2.2: Molecular diffusion of methane in a coal matrix

The diffusion process in the micropore system is described using Equation 2.2 shown below, which is derived from Fick's Law

$$q_{gm} = \frac{8\pi D V_m}{sf^2}\left(C_m - C(p)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

Where:

q_{gm} = Gas production rate from the coal matrix. SCF/day

D = Diffusion coefficient, ft^3/day

V_m = Matrix volume, ft^3

s_f = Fracture spacing. ft

C_m = Matrix gas concentration, Scf/ft^3

$C(p)$ = Equilibrium concentration at matrix-cleat boundary, SCF/ft^3

This equation describes the rate of flow from a matrix element into the cleat system in response to a methane concentration gradient. The proportionality constant in Fick's Law is called the diffusion coefficient *(D)* and it is determined by desorbing methane from a core in a laboratory and measuring the rate of desorption as a function of time.

Diffusion effects can be quantified by determining a sorption time, τ (days), which are related to cleat spacing, s_f (ft) and the diffusion coefficient *D* (ft^3/day). Sorption time is referred to as the time required for methane molecules to desorb off the coal surface and diffuse through the coal into the cleat system. In coals, this time can vary from less than one day to 300 days depending on coal composition, rank and cleat spacing (Boyer C.M. et al., 1990). Sorption time can be calculated as shown in Equation 2.3.

$$\tau = \frac{s_f}{8\pi D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.3)$$

The methane flow in coals starts by lowering the pressure in order to produce the free gas and water from the natural system and to desorb methane from the cleat surface. The variation in concentration is compensated by releasing gas from the matrix by diffusion. Desorption is controlled by pressure gradients while diffusion is controlled by

concentration gradient. Once the gas reaches a cleat or fracture, the flow of the methane through the coal can be described using Darcy's Law. Darcy's Law is being applied to reservoirs with the simultaneous flow of more than one fluid by including the effective permeability to each flowing phase (GRI, 1996). The relative permeability of each fluid (gas and water) should be well known in order to get accurate results.

2.2 Langmuir Isotherms

The basis for CBM reservoir engineering is the Langmuir Isotherm equation which can be written as shown in Equation 2.4. The Langmuir Volume (V_L) or Maximum adsorbed volume is the maximum volume (normally measured under standard temperature and pressure) adsorbed per unite volume of the reservoir at infinite pressure, and the Langmuir Pressure (P_L) is the pressure at which the total volume adsorbed is equal to one half of the Langmuir Volume (V_L).

$$V = V_L * \frac{P}{P_L + P} \quad \text{.....(2.4)}$$

where:

V = volume. SCF/ton

P = Pressure, psia

V_L = Langmuir Volume, scf/ton

P_L = Langmuir Pressure, 1/Psi

It relates the capacity for coal to store gas to the external pressure of the gas. This information is required to predict the volume of gas that will be released from the coal as the reservoir pressure is reduced during continued production. The gas storage capacity is a function of the rank of coal, temperature, the moisture content of the coal matrix, and pressure. The Langmuir isotherm is evaluated at a constant reservoir temperature. A form of Langmuir isotherm that can be used for both single component and multicomponent gases is given by the Equation 2.5 below.

$$G_s = V_L[1-(a+w_c)]\left[\frac{P_L}{P_L+P}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

Where:

G_s = gas storage capacity

V_L = Dry, ash-free Langmuir storage capacity, scf/ton

a = Ash content, weight fraction

w_c = Moisture content, weight fraction

P_L = Langmuir pressure, 1/psi

P = Pressure, psia

At low pressures the relationship between storage capacity and pressure is linear and is referred to as Henry's Law Isotherm, while at very high pressures the storage capacity will reach its maximum value equal to Langmuir storage capacity.

If a sufficient number of molecules are not available, some storage sites will remain unoccupied.

2.2.1 Factors Affecting the Sorption Isotherm

The factors that affect the sorption isotherm are:

- **Ash Content**: The ash content is included in Equation 2.5 because non-coal components reduce the gas storage capacity of coal, hence acting as a diluent. Storage capacity measurements are generally performed on a coal sample with ash content different from the average ash content of the reservoir. In coal samples with significant sulfur content, the ash content is not equal to the mineral matter content of the coal. This is because the procedure used in determining the ash content by burning the sample also vaporizes sulfur, hence it maybe more accurate if the ash content (a) in Equation 2.5 is being replaced with the mineral matter content from the Parr formula shown below;

$$m_c = 1.08a + 0.55s_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2\text{-}6)$$

where:

m_c = Mineral matter content, weight fraction (dry)

s_c = Sulfur content, weight fraction (dry)

- **Mntoisture Content**: water competes for the sorption sites with other molecular species and reduces storage capacity of non-water molecules.

  Laboratory results often present the Langmuir volume on a dry, ash-free basis. Moisture content has been shown to decrease the storage capacity in methane until the critical moisture content is reached. Above this critical moisture level, it is generally believed that there is no further decrease in the storage capacity of methane. The critical moisture level is often assumed to be the same as the equilibrium moisture content.

  A relationship is given for the correction of moisture content below the critical moisture level to the gas storage capacity by the Equation *2-7* below;

$$1-\frac{G_{sw}}{G_{sd}}=\frac{w_c}{w_c+4.35} \quad \text{.....(2-7)}$$

  where;

  G_{sw} = moisture gas storage capacity, scf/ton

  G_{sd} = Dry gas storage capacity, scf/ton

  An equation of this form may be applicable to coals rather than those of the original study. The value 4.35 in the equation should vary from one coal to another and should be estimated by measuring the gas storage capacity as a function of moisture content for the coal of interest. The critical moisture content can equally be estimated from the oxygen content by using the Equation 2-8 below, with the relationship being verified for the coal of interest.

$$w_{cc}=\frac{x_o+1.51}{3.98-0.229x_o} \quad \text{.....(2-8)}$$

where;

w_c = Critical moisture content, weight fraction

x_o = Oxygen content, weight fraction *(oxygen content is determined from an ultimate analysis of the coal sample as specified by ASTM standards).*

- **Temperature:** The sorption isotherm is strongly affected by changes in temperature for a given coal sample. Theory indicates that the Langmuir storage capacity (V_L) is unaffected by temperature, that is the total number of storage sites is insensitive to changes in temperature. The value of the Langmuir constant (b) is being affected by changes in temperature. An increase in temperature will decrease the value of the Langmuir constant, which means at a fixed pressure the amount of gas stored will decrease as temperature increases. Even though isotherms can be adjusted to account for the effects of temperature, it is easier and more reliable to measure isotherms at reservoir temperature.

- **Gas Composition:** Gas produced from coal often contains significant amounts of carbon dioxide, nitrogen, water and heavier molecular weight hydrocarbons. Methane isotherms can result in estimate of pure methane storage capacity that is different than the estimate of the total gas content.

2.2.2 Measuring Sorption Isotherms

In measuring Sorption isotherms, two procedures are involved; First of all the samples are being selected and then prepared according to ASTM standards and secondly isotherm tests are being preformed.

2.2.3 Sample Selection and Preparation

In selecting and preparing samples for testing, some procedures are followed which are shown below;

1. ***Selecting Samples***. Samples used for isotherm tests can either be obtained from drill cuttings or cores. Samples are generally selected on the basis of depth and ash content. Ash-free samples are relatively desired for the test so as to minimize the influence of non-coal materials on the results. In order to characterize the average reservoir behavior, composite samples created by mixing samples from other coal seams or coals of different ash content to create the desired average coal content are prepared.
2. ***Crushing Samples***. Samples are dried and crushed to reduce the time for the test, by minimizing the distance the gas molecules most diffuse through the coal matrix. A sieve analysis should be performed to determine the particle size distribution of the sample and a minimum of 300 grams of crushed samples should be prepared for the various measurements. The preparation procedure is described in the ASTM standards. Crushing the coal changes the surface area for gas adsorption by less than 0.3 percent which is not believed to affect the accuracy of the gas storage capacity.
3. ***Performing Proximate Analysis.*** Proximate analysis is normally performed before and the isotherm test to determine the moisture content, volatile matter content, ash content and fixed carbon content of the coal. This analysis is a standard coal analysis technique with procedures specified in detail by ASTM. The pure coal content of the sample is equal to one minus the moisture plus ash content. It is preferable to select samples with ash content of fifteen percent or less to avoid non coal effects on the diffusion behavior.

   During the moisture content analysis the change in weight resulting from drying a one gram sample at 104-110.5 ^{o}C for one hour is determined. From the ratio of loss in weight during the test to the original weight, the moisture content is determined.

   The volatile matter is determined by measuring the loss in weight resulting from heating a coal sample for seven minutes at 950.5 ^{o}C in the absence of air.

   Ash is the residue remaining after burning coal and coke. During the ash content test procedure a sample is heated to 750.5 ^{o}C over a period of two hours and maintained at this temperature for an additional two hours.

4. ***Performing Ultimate Analysis.*** An ultimate analysis is being performed in addition to the proximate analysis. The results from this test can be used to correlate the critical moisture content. The sample used in this analysis is selected from the same air dried samples used in the proximate analysis. An ultimate analysis consists of three separate tests named below;
   (i) To determine the carbon and hydrogen content,
   (ii) Sulfur content and,
   (iii)Nitrogen content.
   While the oxygen content is determined by difference.
5. ***Determining Moisture Content.*** The isotherm data are strongly influenced by coal composition, temperature and moisture content. The largest source of error is the moisture content because the coal ash content and reservoir temperature are usually known within accepted accuracy. The ASTM procedure is recommended to reproduce the reservoir moisture content.

2.2.4 Performing Isotherm Tests

The equipment required to measure sorption isotherms is a modified Boyle's law proximate maintained at a constant temperature with a water or oil bath. This apparatus consist of the following;

- Stainless steel reference cell, typically 80 cm^3 in volume,
- Stainless steel sample cell, typically 160 cm^3 in volume,
- An appropriate valve to connect the cells,
- An electronically controlled temperature bath in which the cells are immersed,
- High precision pressure transducers to measure the pressure in the cell,
- Internal temperature monitoring to ensure stability of the sample cell during the test.

Table 2.1 shows a summary of the sorption isotherm test procedures;

Table 2.1: Sorption Isotherm Test Procedures.

Step	Description
1.	Calibration of the apparatus to determine the sample cell void volume.
2.	Charging the reference cell to a pressure greater than the expected final pressure Of the sample cell at the current isotherm step.
3.	Opening a valve between the reference cell and the sample cell thereby allowing the pressures to equalize.
4.	Monitoring the sample cell pressure to determine when the pressure stabilizes and adsorption is complete at the current step.
5.	Repeating steps 2 through 5 until the final cell pressure is reached.
6.	Measuring a desorption isotherm if desired.

Isotherm Test Results

At the conclusion of the adsorption isotherm measurement (increasing pressure steps), a desorption isotherm can be measured with decreasing pressure steps.

For pure gases the Langmuir isotherm obtained from desorption data is equivalent to that obtained by adsorption as the process is reversible. Upon completing the test, the changes in weight is being determined and the coal sample is being reweighed due to slight moisture changes.

Hysteresis between adsorption and desorption data for pure gases can be caused by a change in moisture content (experimental errors).

Multi-component gases exhibit hysteresis due to different equilibrium gas temperature within the sample cell at each pressure step.

Data Analysis

The Langmuir equation can be rearranged into a linear form as shown below;

$$C = V_L \frac{P}{P_L + P}$$

$$\frac{1}{C} = \frac{P_L + P}{V_L P}$$

$$\frac{1}{C} = \frac{P_L}{V_L}\left(\frac{1}{P}\right) + \frac{1}{V_L}$$

A straight line plot of the inverse of gas constant (1/C) versus the inverse of pressure (1/P) is made as shown in Figure 2.3. The Langmuir isotherm constants can be obtained from this straight line plot. The intercept of this straight line plot is $1/V_L$ and the slope of the line is P_L/V_L as shown in the figure below.

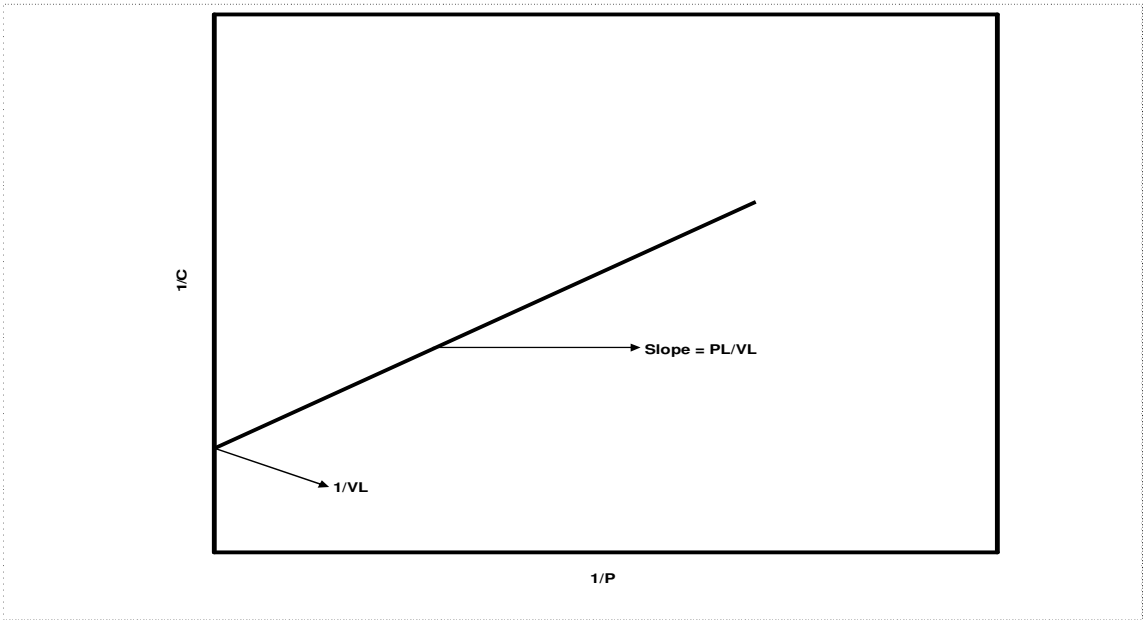

Figure 2.3: Analyzing Langmuir Isotherm Constants

Sorped Gas Volume Correction

Measurements of sorption capacity must account for the reduction in cell void volume as the coal sample sorbs gas. Because this void volume effect becomes noticeable at moderate pressures and significant at high pressures, a correction has been made. Equation 2.9 below expresses the correction of the sorped fluid volume.

$$G_s = \frac{G_s^{'}}{\left(1 - \frac{\rho_f}{\rho_s}\right)} \quad \text{..... (2-7)}$$

where;

$G_s^{'}$ = Uncorrected laboratory estimate of gas storage capacity, scf/ton

ρ_f = Density of gas in the free state at the measurement pressure and temperature, g/cm^3

ρ_s = Apparent density of the gas in the sorbed state, g/cm^3

2.2.5 Problems with Measurements

Some of the problems or errors encountered during sorption isotherm measurements are as follows;

- The depth of origin of drill cuttings is not precisely known and samples may not be the representative of the producing interval.
- Samples with ash content of more than fifteen percent are less likeable to avoid non-coal effects on the diffusion behavior.
- Conditions which are not representative of the reservoir usually results to major errors when measuring the gas storage capacity.
- The moisture content is the largest source of error because the coal ash content and reservoir temperature are usually known within acceptable accuracy.
- At very high pressures, void volume effect becomes very significant.

2.3 Coalbed Methane Production

Coalbed methane reservoirs exhibit three phases of production during their life-time. This behavior differs significantly from the typical decline curve of a conventional gas well. A typical production profile of coalbed methane well is shown in *Figure 2.1*

The inclining gas rate trend in the early life of a coalbed methane well occurs because water initially occupies the fracture (cleat) system of a reservoir, which controls flow to the well. Water must be removed from the cleat system before gas can effectively flow into the well. This process is called *dewatering*. The major physical properties that affect the efficiency of the dewatering process are (GRI 1996):

- Spacing and continuity of the fracture systems quantified by permeability.
- Adsorbed gas content, which is the amount of gas stored in the coal organic material.
- Relative permeability and capillary pressure curves, as a result of the interactions between gas, water and the organic coal matrix.
- The propensity of the coal organic matrix to release stored gas, which is quantified by the diffusion coefficient and the desorption isotherm.

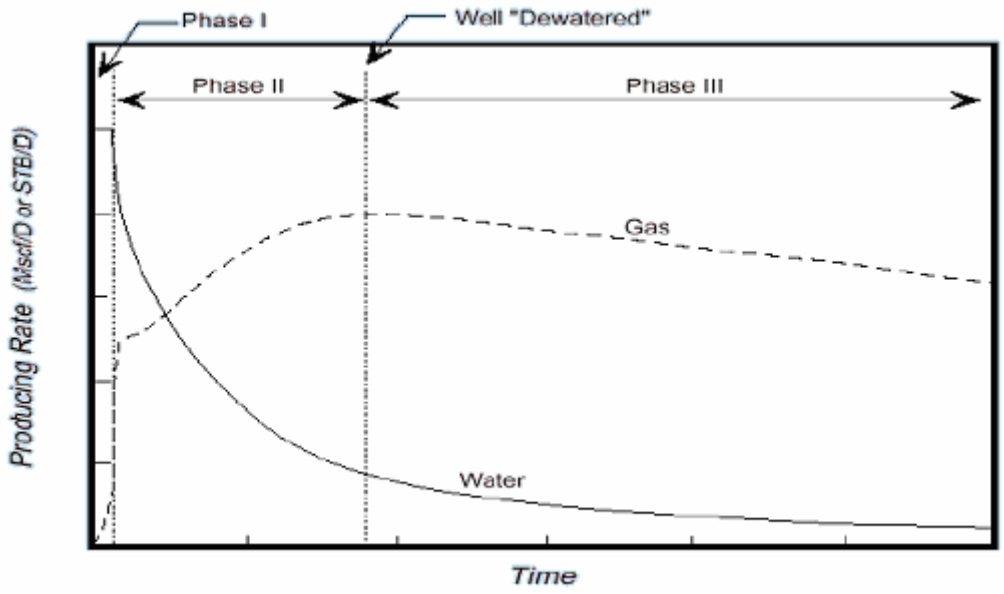

Figure 2.4: Typical Gas and Water Rates during Three Phases of Production From CBM Reservior

The **phase I** of coalbed methane production is characterized by a constant water production rate and a declining flowing bottomhole pressure. Most CBM wells are naturally water saturate because water liberation occurs during the coalification process. Because the water is occupying the principal cleat network, this water must be removed from the major fracture system before the gas can be produced. The water removal or production will relieve the hydraulic pressure on the coal in order to start the production by desorption of the gas on the coal (dewatering). The number of days for this dewatering process to take place or the amount of produced water can vary widely. During this phase the gas is 'pumped -off' and the gas rate maybe inclining as shown in Figure 2.1. The gas rate may also decline depending on the near-well relative permeability characteristics of the reservoir. At the end of Phase I, the well has reached its minimum flowing bottomhole pressure.

Phase II is characterized by a drastic decrease in the water production rate and an increase in the gas production rate. Several other dynamic changes in the reservoir flow conditions take place in Phase II:

- There is a decrease in water relative permeability.
- There is an increase in the gas relative permeability.
- Outer boundary effects become significant (pseudo-steady state flow).
- A dramatic change in gas desorption rates.

Phase III begins only when reservoir flow conditions have stabilized, the well has reached its peak gas rate and gas production is characterized by a more typical decline trend. At the beginning of this phase, the well is considered to be "dewatered" due to water production being very low and/or negligible and also a little change in the gas and water permeabilities. The pseudo steady state exists for the rest of phase III.

2.4 Type Curves

Previous studies (Aminian et al 2004) have analyzed the behavior analyze the behavior of Coalbed Methane reservoirs. A set of type curves were developed to efficiently and

economically analyze and forecast the performance of CBM reservoirs both during dewatering and stable gas production phases, as shown in Figure 2.5.

The objective of these studies was to develop this study in the past was to develop a simple and reliable tool to predict the performance of CBM wells in order to evaluate the economic feasibility and to maximize potential recovery.

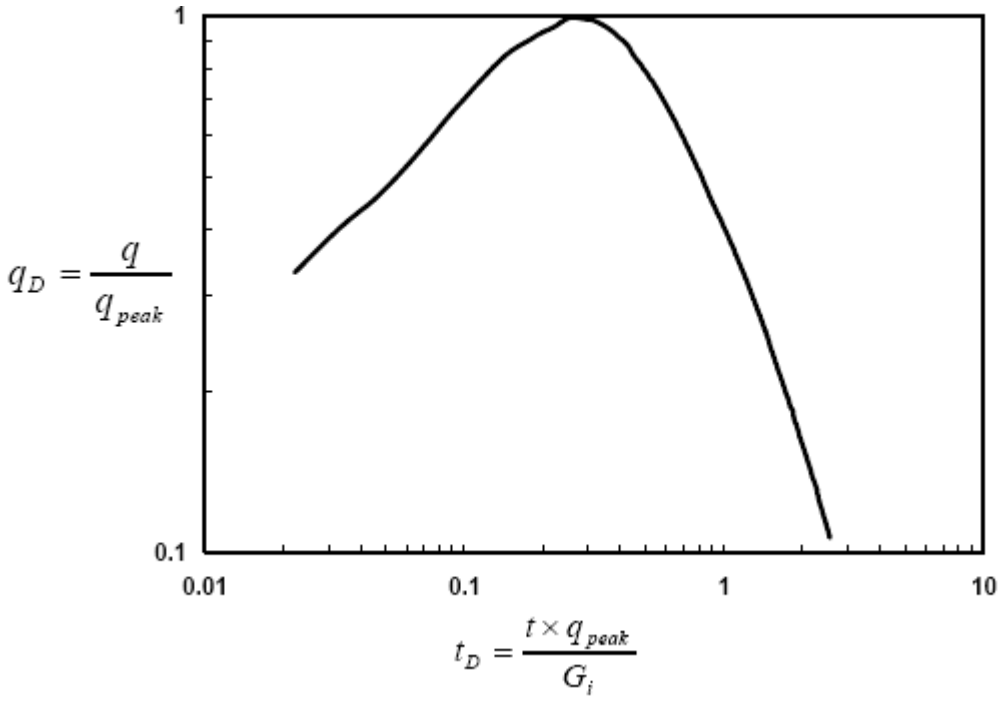

Figure 2.5: Gas production Type Curve

During this study, a reservoir model that incorporates the unique flow and storage characteristics of coalbed methane reservoirs was employed to develop the type curves. During this study, a computer simulator was used to build a CBM model based on the geological characteristics of the Northern Appalachian Basin in order to maximize potential gas recovery (Aminian et al 2004).

2.5 CMG Simulator

CMG (Computer Modeling Group) model is computer software for reservoir simulation and it is capable to determine reservoir capacities in order to maximize potential

recovery. CMG consist of six basic applications;

a) IMEX: Black Oil Simulator

b) STARS: Steam Thermal Advance Processes

c) WINPROP: Phase Behavior Analysis

d) BUILDER: It is a pre processing application used in the reservoir simulation models. It makes the design and preparation of reservoir models faster and more efficient than ever before. Builder provides a window interface which organizes data the way the engineer sees it. Builder presents two models which are; GridBuilder and ModelBuilder. The GridBuilder is used to create simulation grids and rock property data for IMEX, GEM and STARs. It allows the user to easily create and edit grids, positioning them with respect to geological maps, interpolating geological structures and rock properties. The grid can be displayed in a variety of 2D and 3D to allow quick checking of the grid correctness and conformance.

   The Model Builder is a Windows-based software that helps the user to prepare input data for the simulators. It presents an easy-to-use visual interface as well as supports direct editing of the data set information within the program itself. It has an automatic error checking and data validation options.

e) GEM: It is a generalized equation-of-state (EOS) based compositional reservoir simulator for modeling the flow of three-phase, multi-component fluids. The GEM is a CMG fully compositional simulator used to model any type of reservoir where the importance of the fluid composition and their interactions are essential to the understanding of the recovery process. It is an essential engineering tool for modeling very complex reservoirs with complicated phase behavior direction which impact directly on the recovery mechanisms employed to optimize the

recovery. CMG has specifically made some modifications to the code in order to use it for coalbed methane reservoirs.

f) RESULTS: It is CMG's set of post-processing applications designed for visualizing and reporting simulator output. With RESULTS, users are able to efficiently analyze the output from CMG, and other simulators, prepare 2D and 3D plots, generate various informative graphs and prepare tables of required information to be included in a study report. It generates quick and easy export to excel spreadsheets for economic analysis and specialized software. RESULTS is compose of two modules; Results Graph and Results Reports.

   Results Graph is a 2D graph of well production and injection data from simulator runs and from common historical production data sources. It is controlled and defined by the user. RESULT 3D is a module that produces high quality scaled 2D and 3D views of all grids based simulator data and links the displayed wells directly to the graphing capabilities of Results Graph. It allows the user control over display both in location and time. It can be accessed directly through Results Graph and vise versa by opening different windows at the same time. By so doing, the user has a complete vision of the plots so as to better understand the performance of the reservoir. Result Reports produces user definable tabular reports of virtually any type of data generated during a reservoir simulation run, including well data reservoir or sector totals and averages, and reservoir grid property data. It can also be used to compare data from different simulation run and to generate ASCII files to input into economic analysis applications or spreadsheets of the user choice.

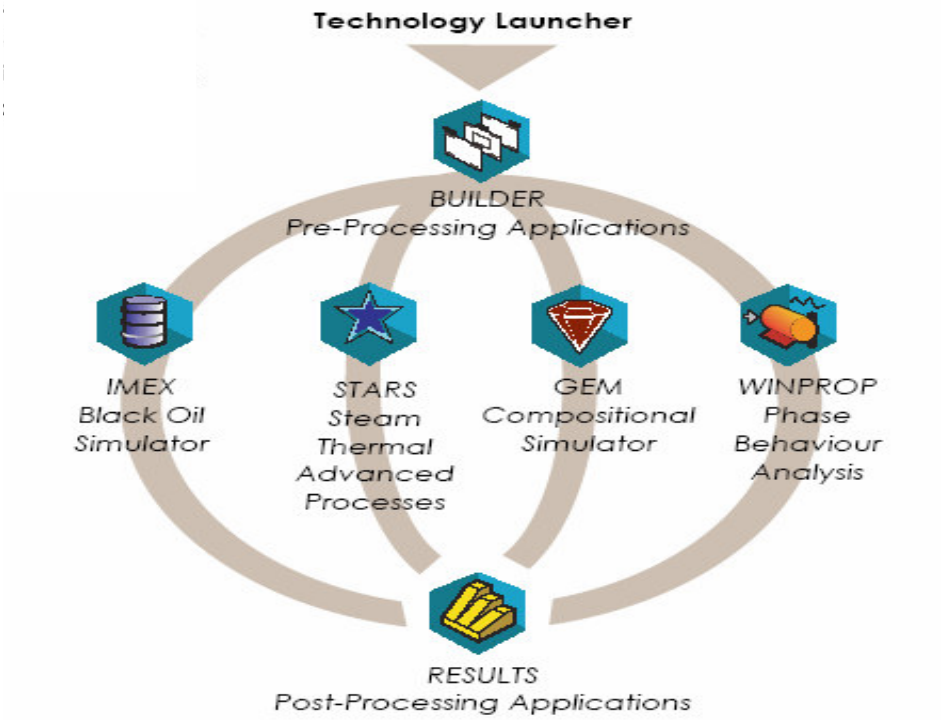

Figure 2.6: Application of CMG

2.5.1 Reservoir Model Description

A two dimensional two-phase Cartesian (CBM) base model was constructed (see Figure 2.7) for an under-saturated CBM reservoir with a well located at the center of the drainage area. The Cartesian model was 13 x 13 blocks each with length 100ft to represent a 40 acres drainage area. GEM is the reservoir simulator software used for this study. This software features a range of dual porosity and dual permeability techniques capable of modeling both coal and shale gas reservoirs. GEM includes options for gas sorption in the matrix, gas diffusion through the matrix, two-phase flow through the natural fracture system.

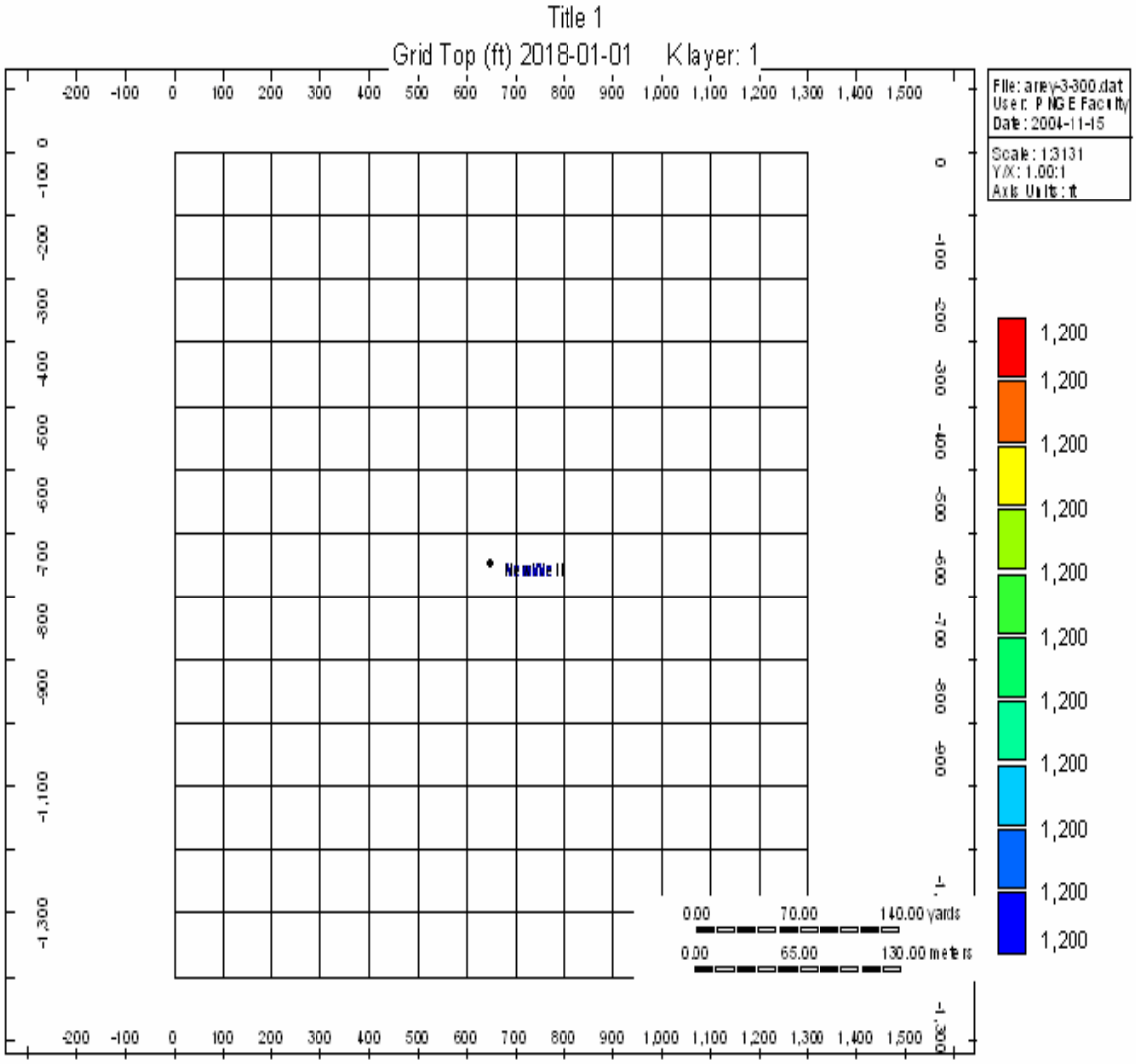

Figure 2.7: Cartesian CBM based Model

During this study, a number of simulation runs were made in order to study the influence of several parameters on the performance of CBM wells. The parameters and values used in the base model are shown in Table 2.2.

Table 2.2: Values and Ranges of Parameters Used in the CBM Base Model

INPUT PARAMETERS	CBM BASE MODEL VALUE
Model	Dual Porosity
Shape Factor Formulation	Gilman-Kazemi
Matrix-Fracture Transfer Model	Pseudo-capillary Pressure with Correction
Model Geometry	2D-Cartesian
Grid Size	100ft x 100ft
Reservior Area	40 acres
Thickness	10ft
Matrix Porosity	0.5%
Fracture Porosity	2%
Matrix Water Saturation	0.5%
Initial Fracture Water Saturation	100%
Matrix permeability	0.01md
Fracture permeability	10md
Fracture Spacing	0.2ft
Initial Pressure	600 psia
Temperature	$113^{o}F$
Langmuir Pressure (P_L)	175.6 psia
Langmuir Volume (V_L)	475 SCF/ton
Coal Sorption Time	50 days
Critical Desorption Pressure	300 psia
Rock Density	$89.63lb/ft^3$
Skin Factor	0
Bottomhole Pressure (Constant)	50 psia

2.5.2 Type Curve Development

The results from the simulation studies discussed in previous section were converted into dimensionless group in order to develop a set of unique type curve. Two sets of dimensionless groups were defined for gas rate, time and peak gas rate using Equation 2.6, 2.7 and equation 2.10 respectively.

$$q_{gD} = \frac{q_g}{(q_{peak})_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

$$t_{gD} = \frac{t \times (q_{peak})_g}{G_i} \quad \ldots\ldots\ldots\

Where:

$(q_{peak})_{gD}$ = Peak dimensionless flow rate

r_e = Radius of reservoir, ft

r_w = Wellhead radius, ft

q_{max} = Maximum flow rate, SCF/D

T = Temperature, ^oR

μ = Viscosity, cp

k = Permeability, md

h = height

P_C = Critical gas desorption pressure pressure, psia

P_{wf} = Bottomhole pressure, psia

S = skin factor

Langmuir isotherm was used to estimate the gas content. It was calculated based on P_L and V_L values at the specific critical desorption pressure (matrix Pressure). Figure 2.8 shows a plot of the Langmuir isotherm used in this study.

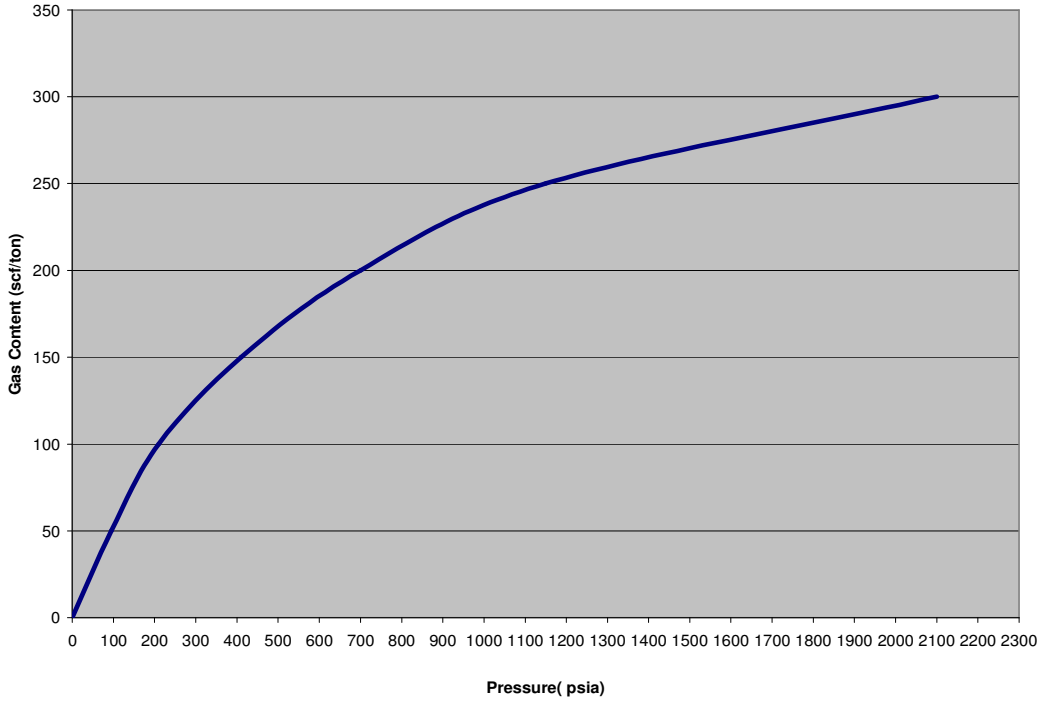

Figure 2.8: Typical Langmuir Isotherm used in Development of Type Curves

Studies had been carried out that indicated values of P_L and V_L are different for different coal (or Basins) could be used in different basins as shown in Table 2.3

Table 2.3: P_L and V_L values for Different Basins

Basin	P_L psi	V_L SCF/TON
Powder River	148	799.8
Powder River	1366.7	866.7
Powder River	315.2	623
San Juan	511.6	163.6
San Juan	231	677.5
San Juan	641.8	741.6
San Juan	90.6	1471.4
San Juan	239	649.1
San Juan	270.1	615.8
San Juan	331.4	980.4
San Juan	334.7	611.5
San Juan	388.5	611
San Juan	309	756.4
San Juan	287.6	671.8
Appalachian	331.9	906.9
Appalachian	150.1	788.8

CHAPTER III

OBJECTIVE AND METHODOLOGY

The objective of this research was to evaluate the impact of Langmuir Isotherms on production behavior on a Coalbed Methane reservoir. In order to achieve the objective, a methodology consisting of the following steps was used:

1. To evaluate the impact of Langmuir isotherm constants on Production Type Curves.
2. To develop a correlation between Langmuir isotherm constants and peak production rate.
3. To verify the accuracy of the type curve and the correlation.

3.1 Evaluating the Impact of Langmuir Isotherms on Production Behavior

The CMG model was utilized to evaluate the impact of Langmuir isotherms on production behavior. The base model was the same as the one described in previous Section (Garcia, 2004). A large number of computer simulations were made by varying Langmuir isotherm (P_L and V_L) constants. For some runs the Langmuir volume was constant and Langmuir pressures were varied while in other runs the Langmuir pressure was constant and Langmuir volumes were varied. The gas flow rate and time obtained from each simulation or run were converted to dimensionless flow rates and dimensionless time using Equation 2.6 and 2.7. This procedure was done in other to observe the impact on type curves.

The first sixteen runs were made using values of Langmuir Isotherm Constants (P_L and V_L) according to Table 2.3. A type curve was developed by plotting the dimensionless flow rate (q_D) obtained from the run versus the dimensionless time (t_D) as shown in Figure 3.1

After which a series of runs were made at constant Langmuir pressures of P_L =150 and varying

Langmuir volumes ranging from V_L = 100 to V_L = 1000. Also the reverse was done with constant (V_L = 475) and changing Langmuir pressures from P_L =100 to P_L =1000 (as shown in

Table 3.1 and Table 3.2 respectively) and type curves were developed for each run. These runs were made so as to evaluate the impact of Langmuir constants on production behavior.

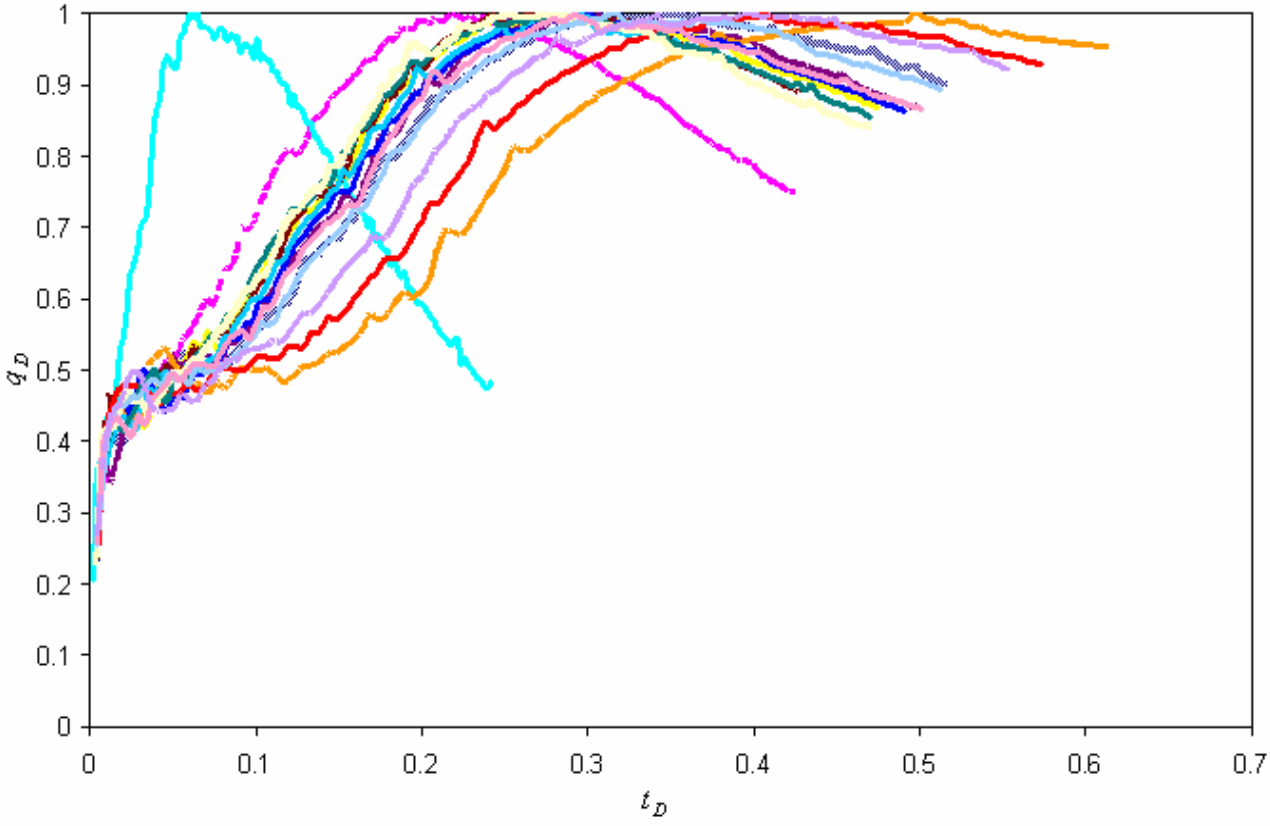

Figure 3.1:Dimensionless Rate Versus Dimensionless Time of Langmuir Constants in Different Basins

3.2 Developing a Correlation between Langmuir Isotherm Constants and peak Production Rate.

In developing a correlation between Langmuir Isotherm constants, and peak production rate, a series of runs were made at constant V_L values and changing P_L values as well as Constant P_L values of 150, 300 500, and 700 psi^{-1} at changing V_L. This time the dimensionless peak flow rate,$(q_{peak})qD$ values were calculated using Equation 3.1 below and plotted against the changing P_L and changing V_L values.

$$(q_{peak})_{gD} = \frac{(q_{\max})_g * 1422T\mu_i Z_i}{kh(P_R^2 - P_{wf}^2)}\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{3}{4} + S\right] \quad \text{.....(3.1)}$$

3.3 To verify the accuracy of the type curve and peak gas rate correlation.

In verifying the accuracy of a type curve, a case study was simulated using the values in Table 3.3. The result was exported to an excel spread sheet as flow rate and time and the following steps were carried out;

1. The gas Constent (G.C.) was calculated and then used to calculate the initial gas in place (G_i=184MMCF) for the case study.
2. At V_L of 600 SCF/ton, the peak dimensionless flow rate was obtained by reading the corresponding value from the correlation for (Figure 4.7) peak dimensionless flow rate versus V_L.
3. The peak dimensionless flow rate for the case study was used in calculate maximum flow rate using Equation 3.1.
4. Production Type Curves were used to predict flow rate and time respectively for the case study by;
    - multiplying the calculated maximum flow rate for the case study by the dimensionless flow rates of the base study to obtain flow rate (q) values for the case study as shown in Equation 3.2,

$$q = q_{\max} \times q_D \quad \text{.....eq 3.2}$$

- the dimensionless time values for the base case was multiplied by the new gas in place value (G_i=184MMCF) for the case study and divided by the maximum flow rate (q_{max}) for the case study to get new values of time (t) for the case study as shown in Equation 3.3.

$$t = \frac{t_D \times G_i}{q_{\max}} \quad \text{.....eq.3.3}$$

5. Production history for the case study and type curve prediction were compared.

Table 3.3: Values used to generate the Case Study

	CASE STUDYVALUES
height	20ft
Depth	1500ft
Fracture Porosity, y Φ (F)	0.04
Matrix Porosity, Φ(m)	0.008
Matrix Permeability, (m)	0.004
Fracture Permeability, (f)	15
Fracture Pressure (f)	800 psia
Matrix Pressure(m)	500psia
Bottomhole Pressure ,BHP	80psia
Fracture. Spacing	0.4
Desorption time	80 days
Langmuir Volume, V_L (CH_4)	0.359 (600scf/ton)
Langmuir Pressure ,P_L (CH_4)	1.48 x 10^{-3} (675.7 psia)
Area	80 acres
Rock Density, ρ	100 lb/ft^3

CHAPTER IV

RESULTS AND DISCUSSION

The general objective of this study is to develop production decline type curves that can account for Langmuir Isotherm constants.

For the first set of runs made using Langmuir Isotherm constants in different basins, a type curve was developed with the curves or each run moving away from each other as shown in Figure 3.1

For the set of runs made from constant P_L of 150 psia and 500 psia at changing V_L from 100SCF/ton to 1000SCF/ton and constant V_L of 475 SCF/ton and changing P_L of 100psia to 1000psia, a type curve was developed for dimensionless flow rate and dimensionless time as shown in Figure 4.1, 4.3, and 4.5 and the log-log plots of these type curves were also made as shown in Figure 4.2, 4.4 and 4.6

The dimensionless peak flow rate of each run made with constant Langmuir volume or constant Langmuir pressure and varying Langmuir pressures or varying Langmuir volumes respectively were calculated as shown in Table 4.1 and 4.2 and plotted against the changing Langmuir pressures and volumes respectively as shown in Figures 4.5, 4.7,and 4.8.

In the series of runs made at varying Langmuir volumes and constant Langmuir pressures of 150 psi^{-1} and 500 psi^{-1}, it can be seen that all the curves made at different Langmuir volumes ranging from 100 scf/ton to 1000 scf/ton converge. While for the runs made at changing P_L and a constant V_L value of 475 scf/ton, the curves produced for each of the ten runs are close together but they do not converge instead they move away from each other at increasing P_L values ranging from 100 psi^{-1} to 1000 psi^{-1} to the right.

For the third series of runs made at constant V_L of 475 SCF/ton, the dimensionless peak flow rate was calculated and plotted against the changing P_L values and was observed that the peak rate decreases at increasing P_L values. For the forth and fifth set of runs made, the dimensionless peak flow rate was calculated for each run and a type curve of peak dimensionless flow rate versus changing V_L values (ranging from 100 SCF/ton to 1000SCF/ton) at constant P_L values of 150, 300, 500 and 700psi^{-1} was developed respectively (Figures 4.7 and 4.8). The curves developed are almost straight lines and they lie parallel to one another. From this type curves produced a correlation between Langmuir Isotherm constant and peak production flow rate is made.

To verifying the accuracy of the type curve and peak gas rate correlation, the flow rate value for the case study (14670.72 SCF/D) was close to the flow rate value for the base case (16455.1SCF/D) and so it was concluded that the type curves are accurate as shown in Figure 4.9.

Table 4.1: q_{peak} converted to $(q_{peak})_D$ for different P_L values at a constant V_L of 475scf/ton.

P_L	q_{peak}	$(q_{peak})_D$
psi	ft3/day	
100	12551	98.3843
200	13381.9	104.8975
300	13422.9	105.2189
400	13134.9	102.9613
500	13055.7	102.3405
600	12529.8	98.2181
700	12277.1	96.2372
800	11676.7	91.5308
900	11484.1	90.0211
1000	10979.4	86.0649

Table 4.2: q_{peak} and $(q_{peak})_D$ for Various Langmuir Volumes at a constant Langmuir Pressure of 150psia.

V_L	Q_{max} (ft^3/day)	$(q_{peak})_{gD}$
100	6239.46	48909.6
200	8672.06	67978.2
300	10674	83670.9
400	12331.5	96663.7
500	13338.2	104554.9
600	14546.4	114025.7
700	15362.4	120422.2
800	16328.1	127992.1
900	17008.1	133322.4
1000	17852.5	139941.5

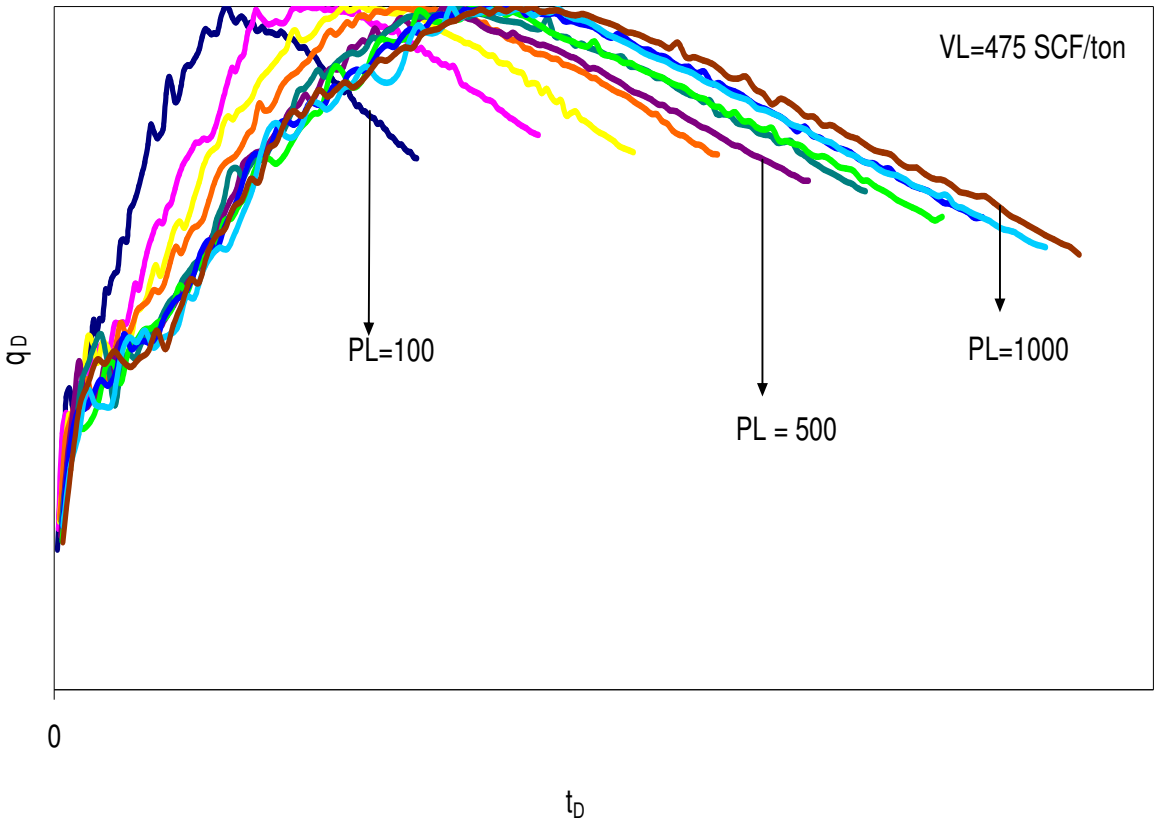

Figure 4.1: Type curve at a constant Langmuir Volume and varying Langmuir Pressure.

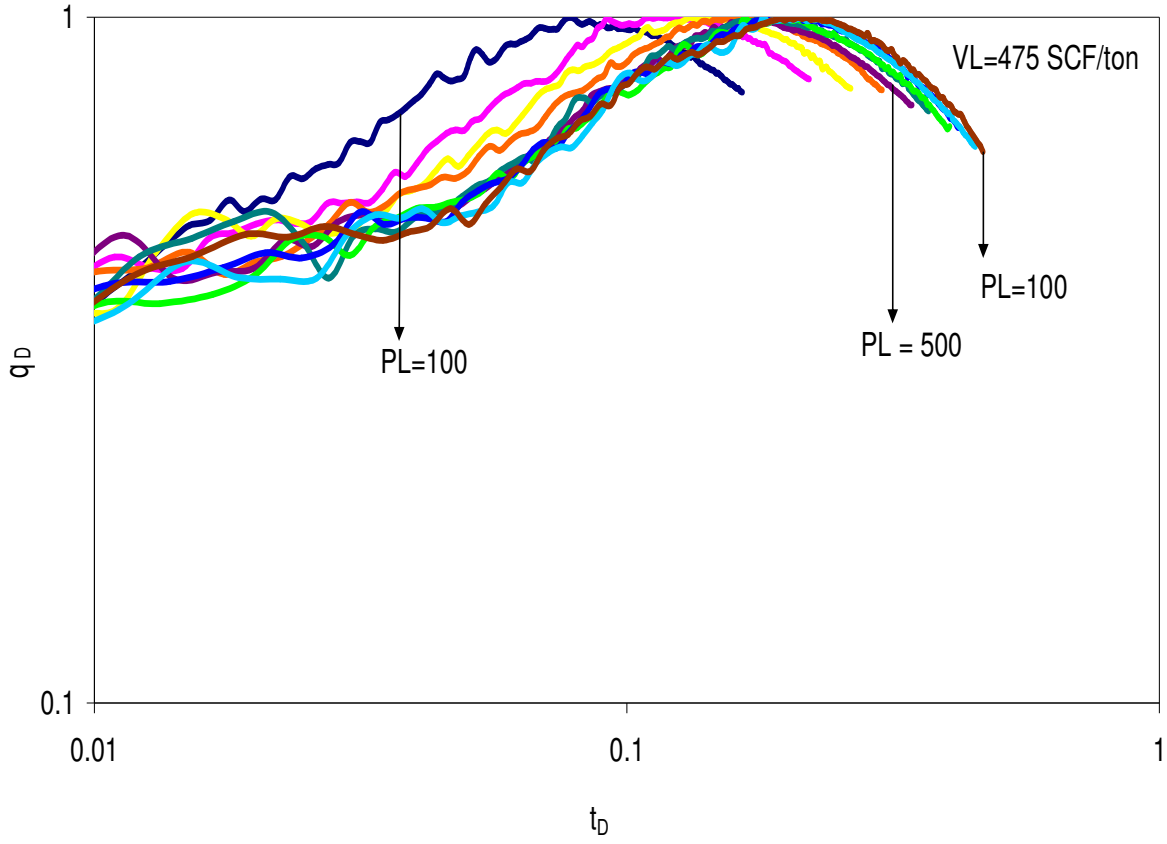

Figure 4.2: A log-log plot of Dimensionless Flow Rate versus Dimensionless Time at a constant Langmuir Volume and varying Langmuir Pressure

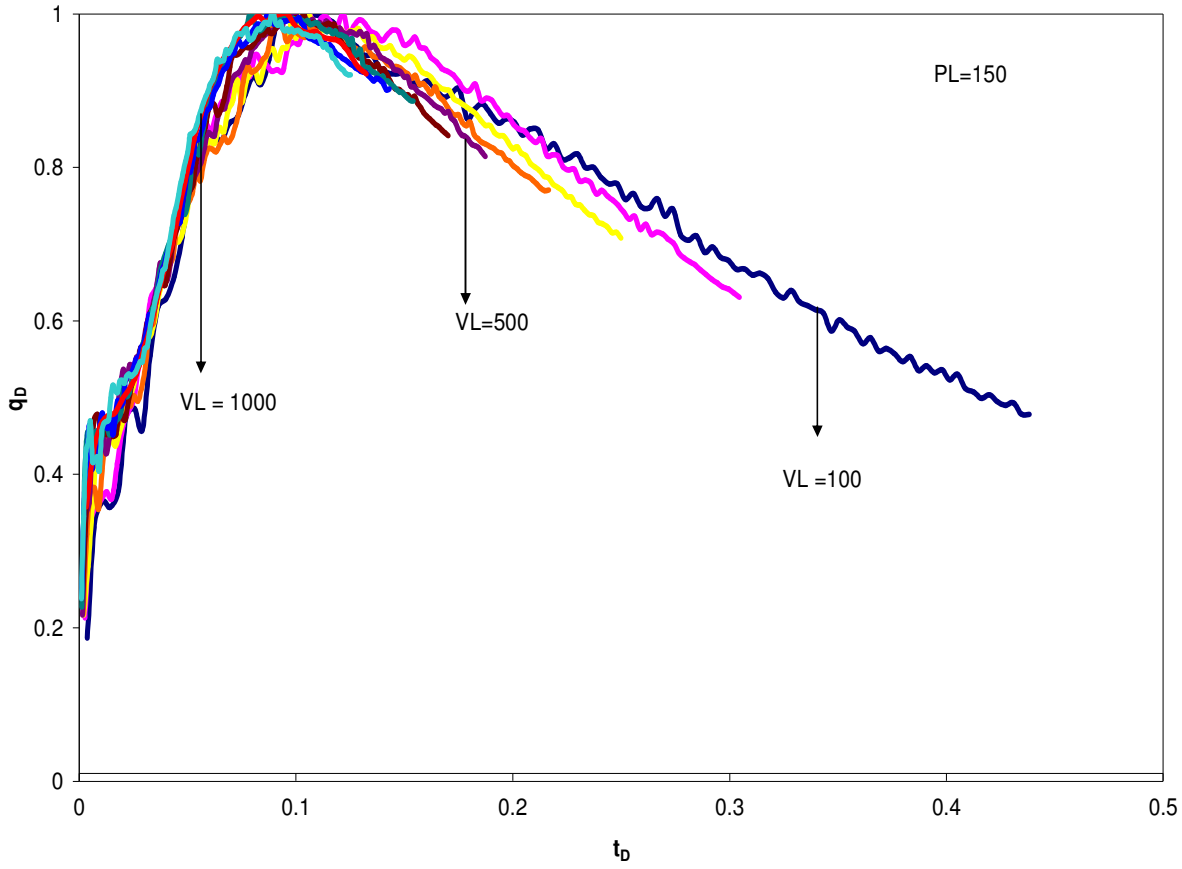

Figure 4.3: Type curve at a constant Langmuir Pressure of 150 psi^{-1} and varying Langmuir Volume.

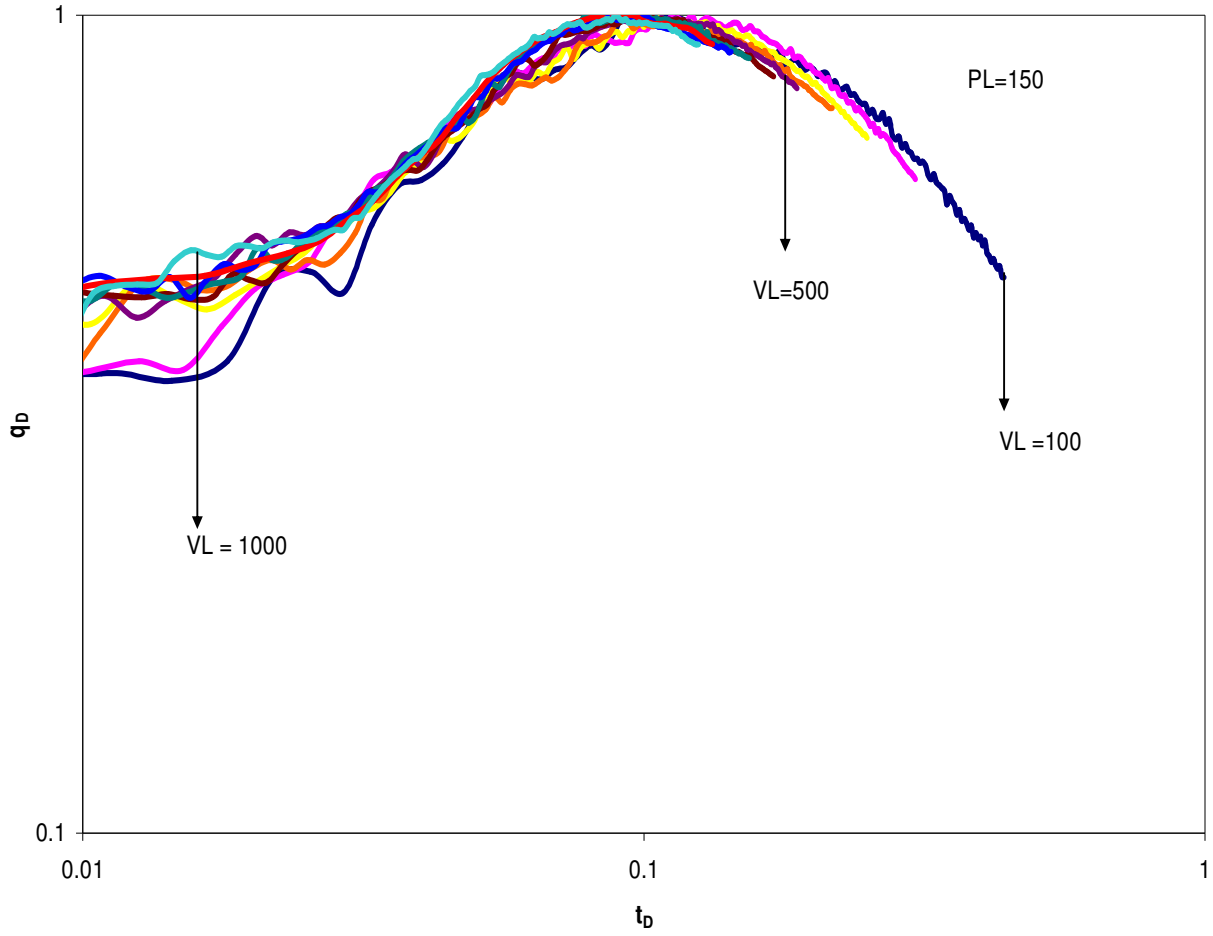

Figure 4.4: A log-log plot of Dimensionless Flow Rate versus Dimensionless Time at a constant Langmuir Pressure of 150 psia and varying Langmuir Volume

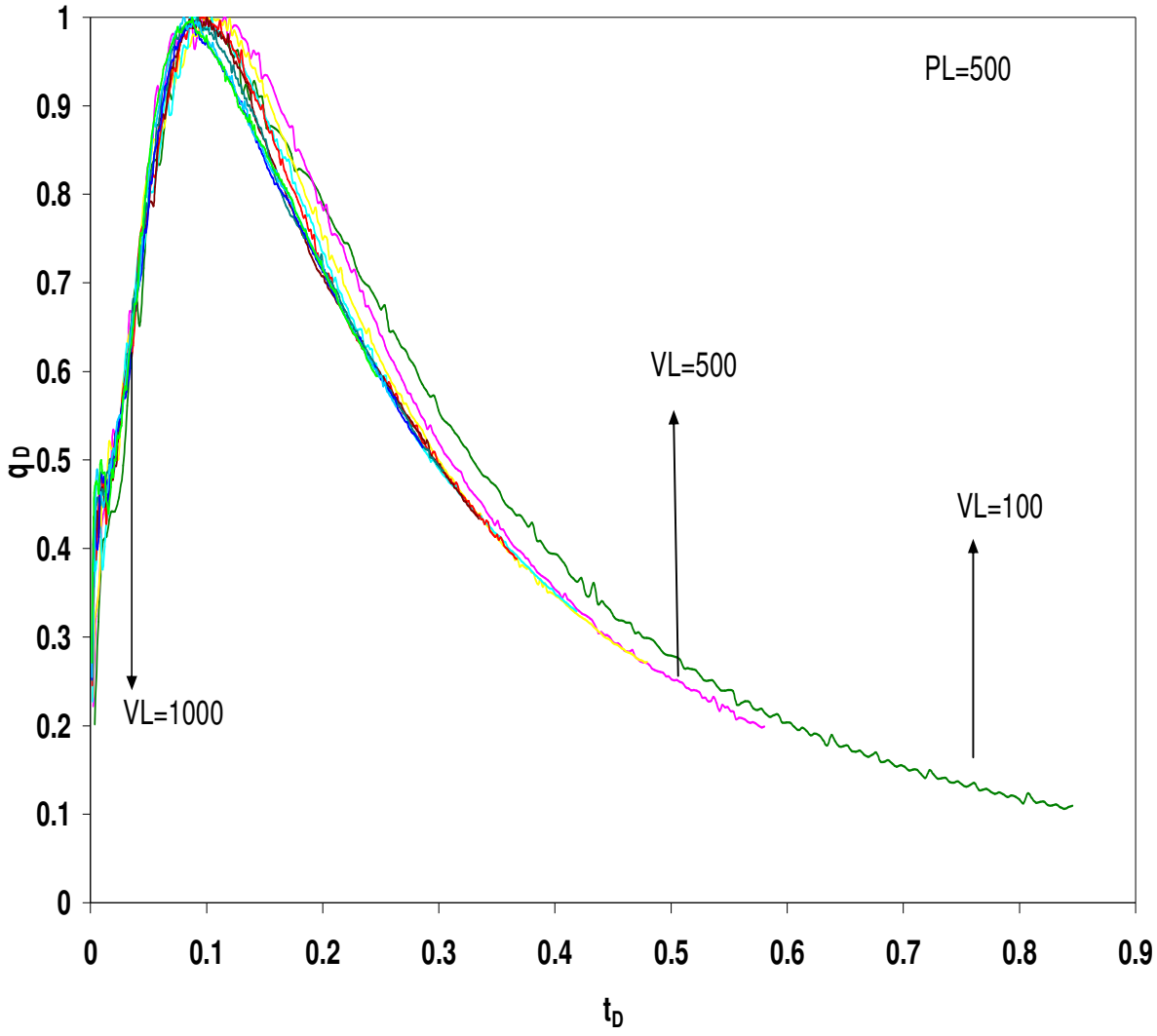

Figure 4.5: Type curve at a constant Langmuir Pressure of 500 psi^{-1} and varying Langmuir Volume.

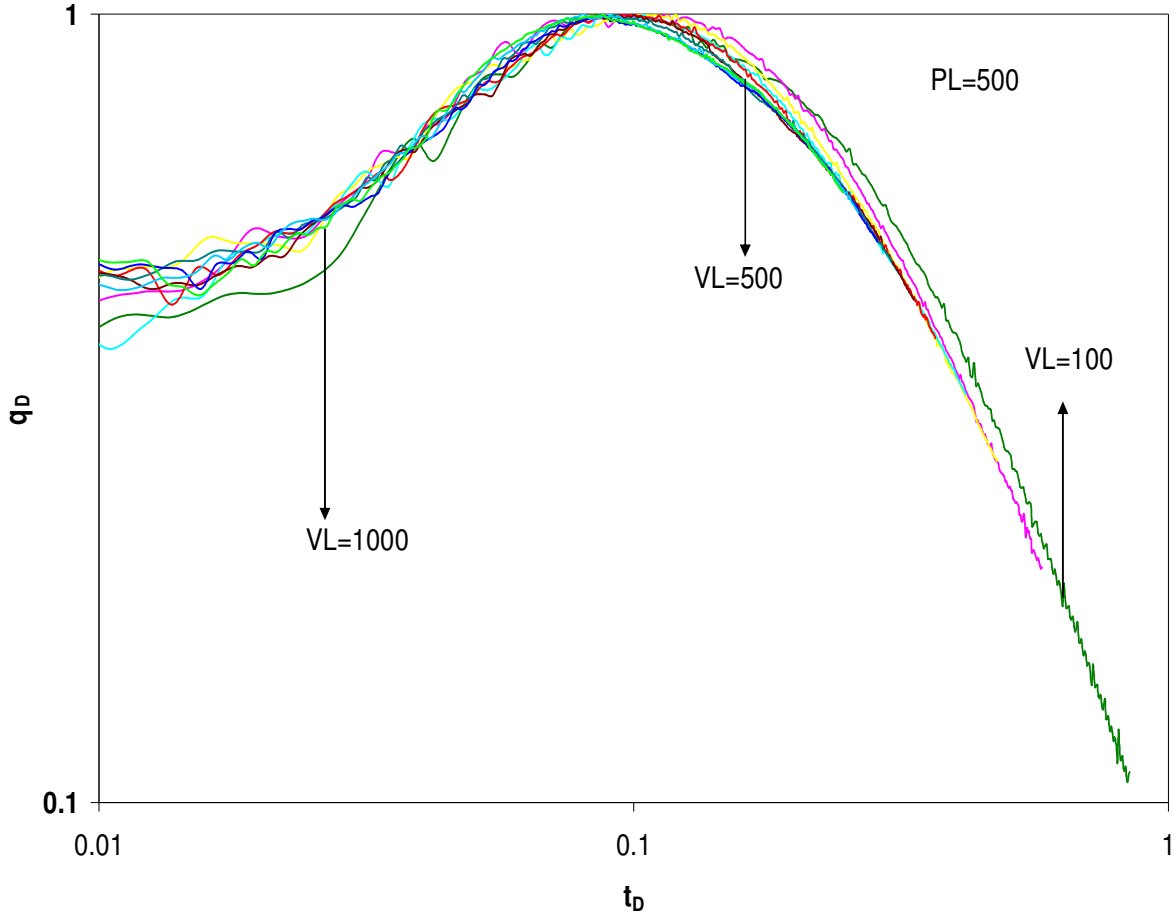

Figure 4.6: A log-log plot of Dimensionless Flow Rate versus Dimensionless Time at a constant Langmuir Pressure of 500 psi^{-1} and varying Langmuir Volume

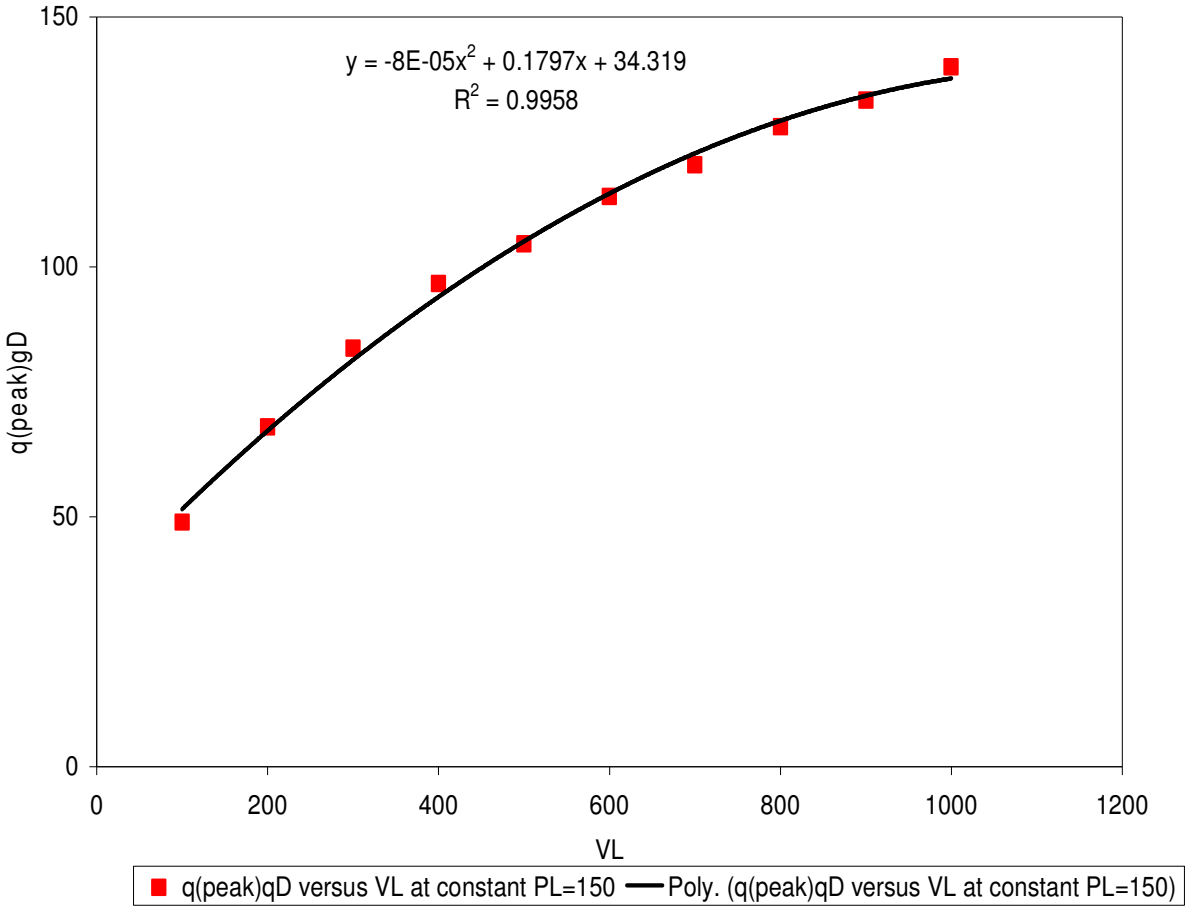

Figure 4.7: Correlation of $(q_{peak})_D$ against V_L at a constant P_L of 150psia.

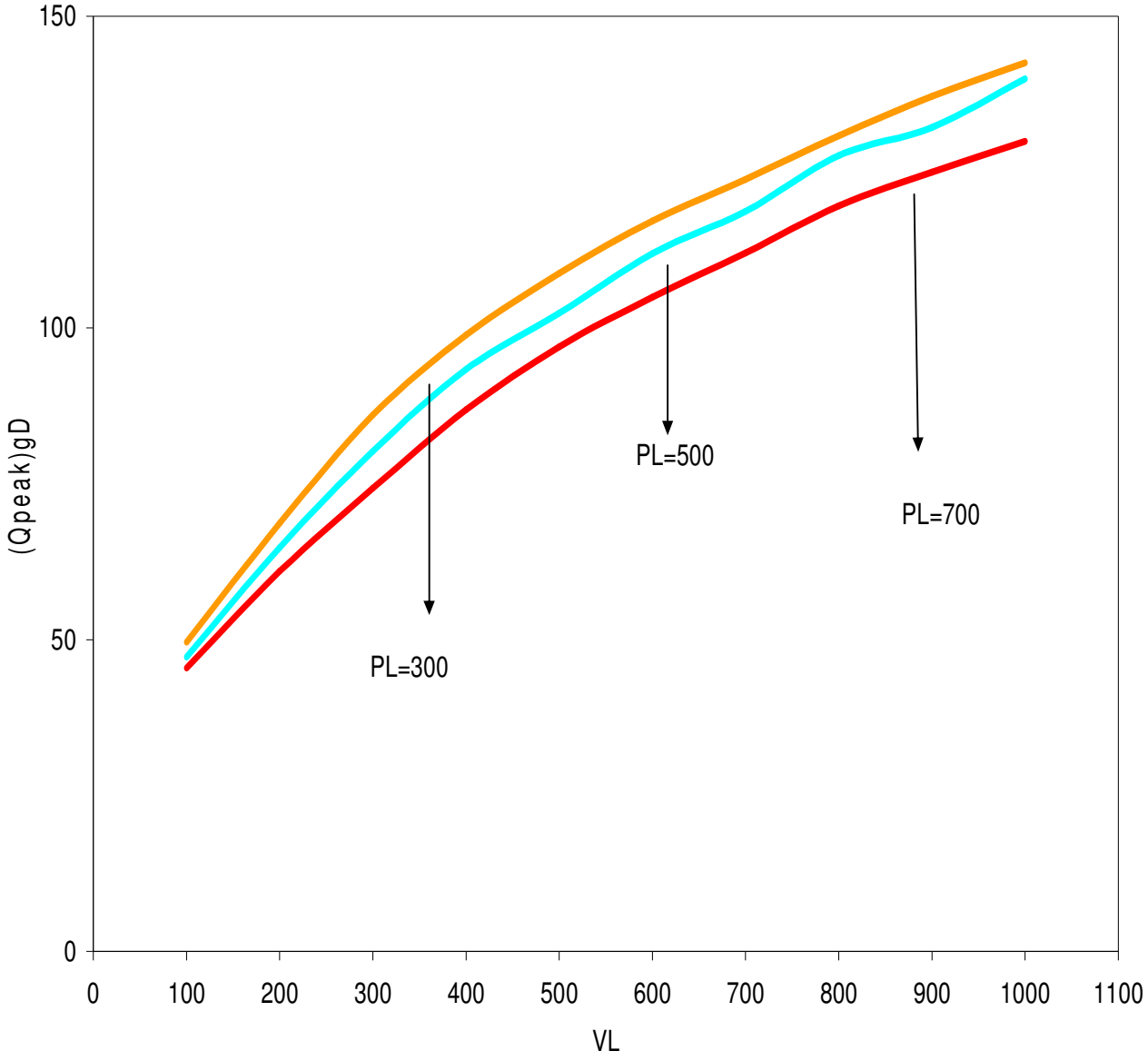

Figure 4.8: Correlation of $(Q_{peak})_D$ against V_L at a constant P_L of 300, 500 and 700 psi^{-1}.

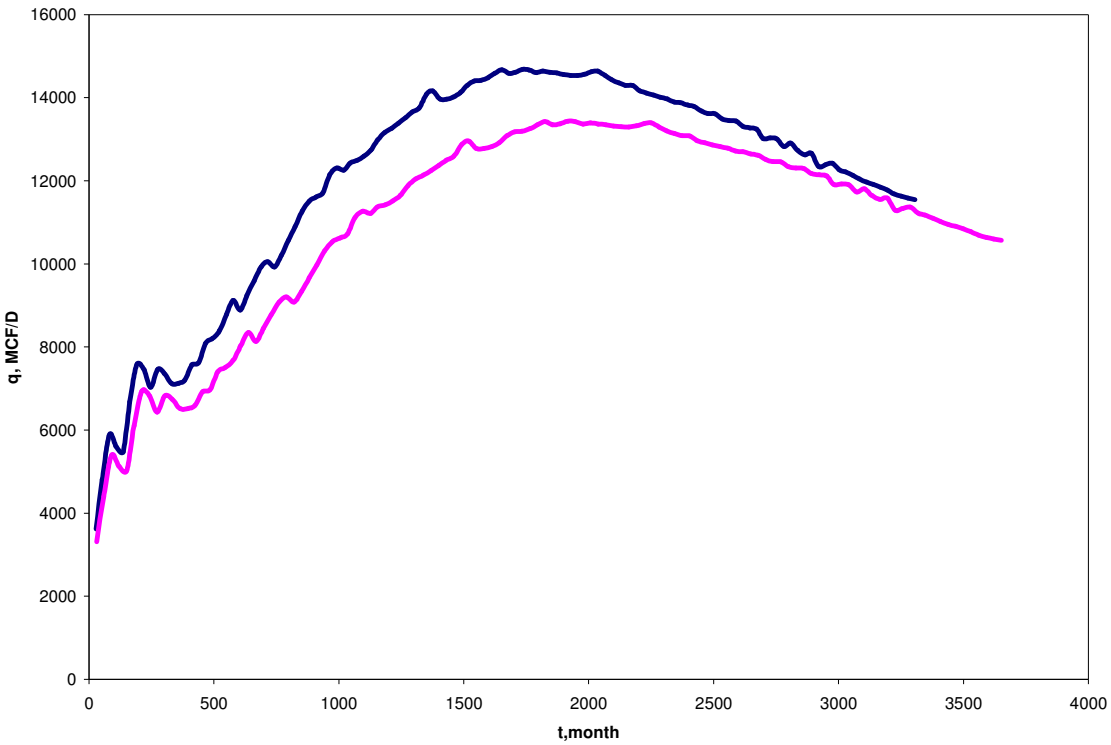

Figure 4.9: Comparism of Production for the case study

CHAPTER V

CONCLUSION AND RECOMMENDATION

In this research, type curves were made on dimensionless flow rate (q_D) and dimensionless time (t_D) by using Langmuir Isotherm constants (P_L and V_L). From this type curves developed, it is concluded that;

1. Changes in V_L values do not have significant impact on the shape of the type curves, that is the curves are clustered together, while changes in P_L values has a major impact on the type curves, that is the curves separate from each other with increasing P_L values.
2. A correlation was developed between peak gas production rate $(q_{peak})_D$ and V_L which shows that peak production rate increases with increase in V_L.
3. The type curves are concluded to be accurate.

RECOMMENDATIONS:

To develop a new set of dimensionless groups can converge the various type curves for different P_L values into one type curve.

This approach has provided an accurate tool that can easily be used by small producers to analyze and forecast the gas production for coalbed methane..

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